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14. ABSTRACT
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Summary of LARC particle asymptotic changes from geomagnetic reference field models: 1955 to 1995

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Abstract

A high-order (10th) mathematical model for the quiescent geomagnetic field from Epoch 1955.0 to Epoch 1995.0 was used to calculate the asymptotic directions of vertically incident cosmic ray particles at the LARC location (62° 12' 09" S - 58° 57' 42" W, South Shetlands, King George Island, Fildes Bay Ardley Cove, 40 m a.s.l.). The digital computer-based studies were made at spaced intervals of rigidity in a wide range extending from a value sufficiently high (20.00 GV), such that free particle access is ensured, to a low value at which it may confidently be assumed that access would be forbidden (2.00 GV) for this Antarctic location. A summary of the obtained results is given.

1 Introduction

Extraterrestrial charged particles reaching a fixed location on the Earth travel along specific paths (*trajectories*) through the geomagnetic field. The

knowledge of the particle direction in free space (*asymptotic direction*). *i.e.* prior to its interaction with the geomagnetic field, is a prerequisite for relating observed cosmic-ray intensity variations at the Earth with the direction of these particles in the near Earth environment (*e.g.* [1] for a review). In order to determine which energies of cosmic ray particles are able to reach a selected geographic location, it is necessary to perform detailed and extensive numerical calculations of particle trajectories in a mathematical model of the Earth's magnetic field (see [2] for an early work). In fact. the Earth's magnetic field provides a shield against the incoming charged particle radiation: the particle energy threshold is high in the Earth's equatorial region, and it goes towards low values when one approaches polar latitudes.

To perform trajectory computations independent of the considered particle species, the energy (E) is replaced by the rigidity (R), *i.e.* the momentum per unit charge. The name *cutoff rigidity* is used to indicate the minimum R value that a charged particle can possess to arrive from a specific direction of free space to a selected measurement point. In other words, the cutoff rigidity is the parameter used for denoting the rigidity value below which no particles can be detected from a specific direction at a selected location. This value is dependent on zenith and azimuthal directions of arrival. Since most of cosmic ray particles are positively charged, there exists an East-West effect in the incoming cosmic ray flux to a detector. with higher cutoff rigidity values to the East, and lower cutoff rigidity values to the West. Hence. there are several parameters to be specified before exploiting any evaluation. They are: (i) the geographic coordinates of the detector site; (ii) the selected zenith direction; (iii) the chosen azimuthal angle; (iv) the altitude of the detector location; (v) the geomagnetic status (quiet or perturbed: which is often described by geomagnetic indices: AE for high, Kp for middle and Dst for low geomagnetic latitudes) at the measurement time and the baseline quiescent geomagnetic field representation for the appropriate epoch.

Calculations should be initiated at a R value well above the maximum expected East cutoff. and continue, at discrete intervals S = ΔR of decreasing R. until the cutoff is certainly surpassed. A careful choice of the R intervals (*i.e.* S) is needed. because for many experimental sites (particularly those at middle and high geomagnetic coordinates) the transition of allowed/forbidden trajectories is not unique. The name *cosmic ray penumbra* is used for denoting the region between the first (which determines the upper rigidity cutoff: R_U) and the last (the lower rigidity cutoff: R_L) allowed/forbidden transition in the rigidity space. Moreover. the effective rigidity cutoff (R_C) is evaluated by subtracting allowed rigidities in the penumbra from the R_U value (see [3], for details on cutoff rigidity terminol-

ogy).

Within such scenario the evaluation of induced effects on cosmic ray particles by the long-term changes of the geomagnetic field at the Antarctic Laboratory for Cosmic Rays (LARC) was initiated. The first results were reported by Storini et al. [4]. This paper presents a more extensive study including the global aspects of the problem.

2 Cosmic ray asymptotic changes for LARC

The 5-year incremented standard models for the quiescent geomagnetic field were used (from Epoch 1955.0/DGRF55 to Epoch 1995.0/IGRG95) for evaluating cosmic ray induced effects by the secular variation of the geomagnetic field at the LARC (62° 12' 09" S - 58° 57' 42" W, South Shetlands, King George Island, Fildes Bay Ardley Cove, 40 m a.s.l.) location. No external fields were considered (see [4] for details and [5] for an attempt in using the Tsyg89 - Tsyganenko/1989 [6] - external field).

We started our trajectory calculations at the top of the atmosphere (assumed 20 km high) and, working backward, we traced a negative proton out through the geomagnetic field model. This corresponds to the trajectory of a positive proton coming from the interplanetary medium through the magnetosphere, impacting the atmosphere at 20 km above the station site and then creating a nuclear cascade down to the detection location on the Earth's surface. The parameters used were:

(i) geographic coordinates: 62.20° S - 301.04° E;

(ii) zenith direction: 0° (i.e. vertical direction);

(iii) azimuth angle: none;

(iv) altitude: not relevant;

(v) geomagnetic status: not considered, because we are interested on effects induced by the main (internal) field;

(vi) S = 1.00 GV for 20.00-10.00 GV, S = 0.10 GV for 9.30-6.30 GV, S = 0.05 GV for 6.25-5.40 GV, and S = 0.01 GV for 5.39-2.00 GV.

From these computations, for every considered epoch, we selected the allowed (particle paths going to the interplanetary space) and forbidden (particle paths intersecting the solid Earth or paths of particles which have
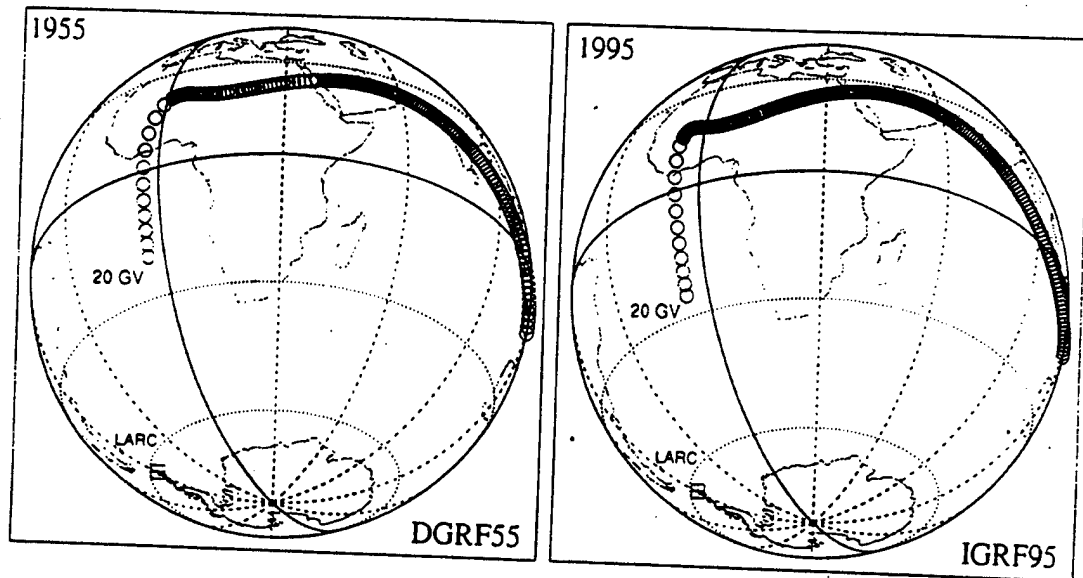
Figure 1: Particle asymptotic directions (circles) at LARC location for 1955 (left) and 1995 (right) epochs. The geographic location of the cosmic ray observatory is indicated by a cross surrounded by a square (as in the other reported figures).

not enough momentum for escaping from the geomagnetic field: the so-called trapped particles) trajectories.

A series of reports were published, giving particle asymptotic directions in tabular form for LARC. They refer to the 1995 [7], 1990 [8], 1985 [9]. 1980 and 1975 [10] years. Figure 1 illustrates the results in an orthographic projection of the Earth (i.e. as seen from far out in space) for the two extreme epochs: 1955 (left panel) and 1995 (right panel). From them, it is clear that until the considered 20 GV particle direction (particle rigidities increase from the right to the left in each panel) the induced changes by the secular variations of the geomagnetic field are significant for LARC location.

Results are better illustrated in fig. 2, where the particle directions in the 5-year step evaluations for discrete R values are reported. Westward (enhanced for R ≤ 8 GV) and Southward (large for R ≥ 11 GV) shifts are evident for all of them. Moreover, the longitudinal spread of particle directions at low rigidities is outstanding. This is confirmed at 4 GV, where the particle direction shifted from the Latin-American sector (1955) to the Asian one (1995). It is a westward shift greater than 240° (see fig. 3).

The global asymptotic directions of the incident cosmic ray particles at the LARC location for 1995, 1990 and 1985 are illustrated in fig. 4 for rigidity
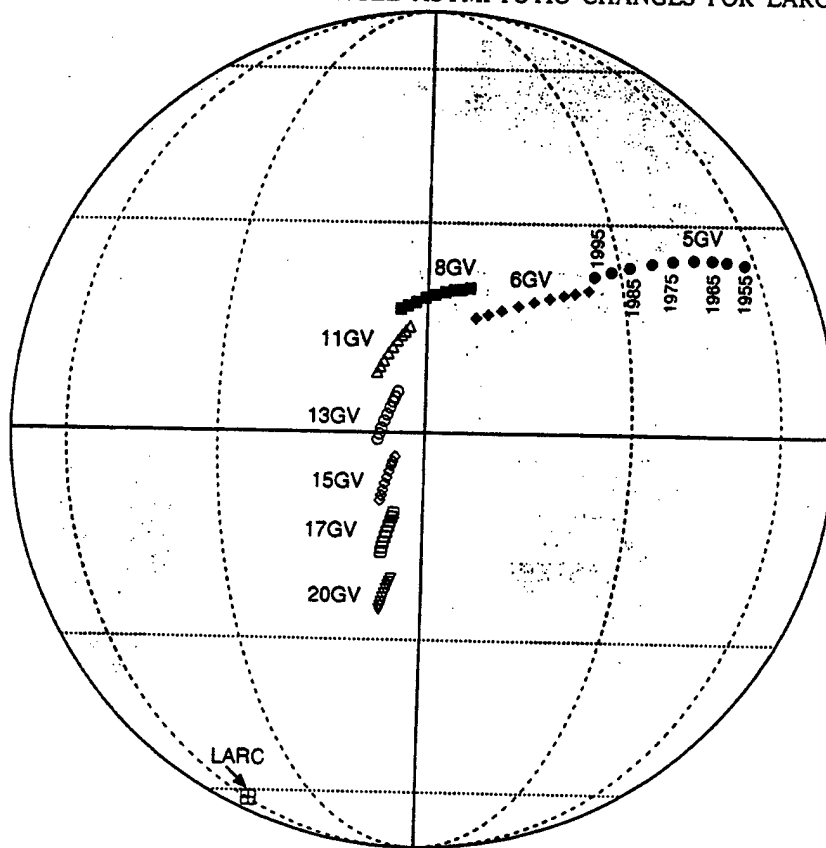
Figure 2: Particle asymptotic directions at LARC location from 1955 to 1995, as derived using the 5-year step geomagnetic field models, for the indicated particle rigidities.

values above the cosmic ray penumbra. These directions are again projected on a map of the Earth (the first 180° of longitude are repeated on the right side to facilitate particle direction identification). Particle directions from 20 GV to 3.31 GV (upper panel), 3.42 GV (middle panel), and 3.54 GV (lower panel) are shown as circles (see the left and right sides of each panel), while a circle surrounded by a square denotes the directions of the last allowed GV interval (central part of each panel): 3.30 GV - 3.21 GV (upper panel), 3.41 GV - 3.32 GV (middle panel) and 3.53 GV - 3.45 GV (lower panel). The Westward shift with the years is clearly evident. Changes in the cosmic ray penumbra are discussed in the next section.

The results shown above for vertically incident charged particles on LARC detector envisage that the original particle direction of approach (far away from the Earth, *i.e.* the asymptotic direction) can be very different

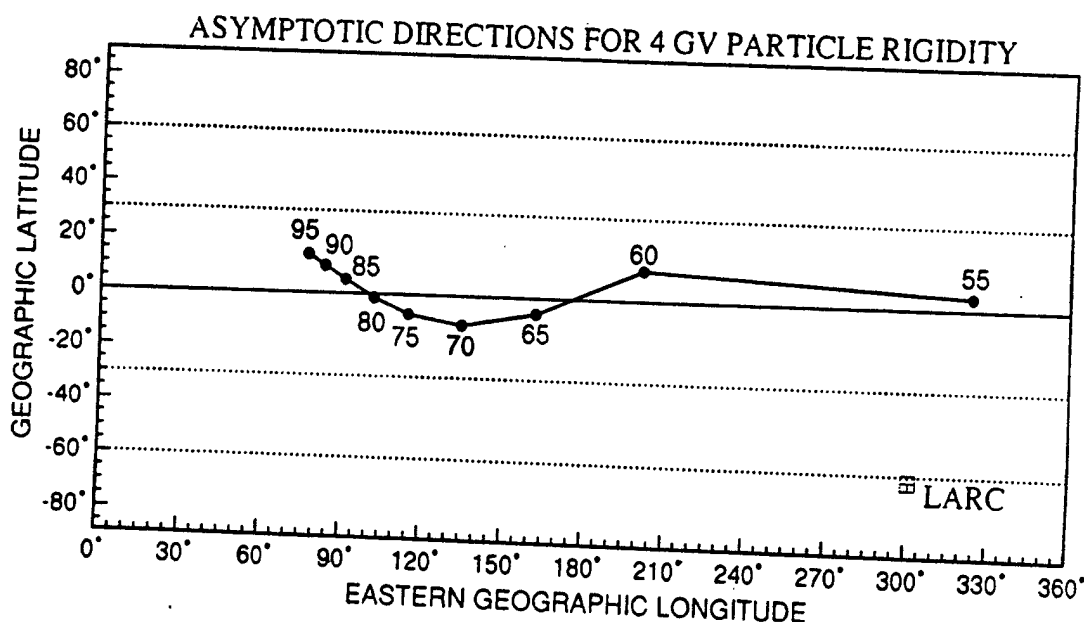ASYMPTOTIC DIRECTIONS FOR 4 GV PARTICLE RIGIDITY

Figure 3: 4 GV particle asymptotic direction, projected on a map of the Earth, from 1965 to 1995 for the vertical direction at the LARC location. Points are joined to illustrate the variability from one 5-year step to the next.

from the considered detector direction. Nevertheless, the detector is receiving all the particles having rigidities exceeding the R_U value (see Sect. 1) and the flux for these particles will be the same as it would have been for a null geomagnetic field. Hence, why do we need cosmic ray asymptotic directions? When space anisotropies are the subject of a research, such as in the case of relativistic solar proton events (the so-called Ground Level Enhancements: GLEs), the forementioned evaluations for many cosmic ray observatories are indispensable.

Nowadays LARC data covers over ten years of measurements (begining of LARC records: January 19, 1991) and data for GLE51 (June 11, 1991) to GLE63 (December 26, 2001) are available at the International Data Centers or directly on request (storini@fis.uniroma3.it; [11]) for use by the scientific community.

3 LARC geomagnetic cutoff or threshold rigidity

Since a long time cosmic ray measurements were shown to be affected by the secular variation of the geomagnetic field. Shea and Smart [12] analysing a thirty-year interval (1935 to 1965) demonstrated that some regions of the
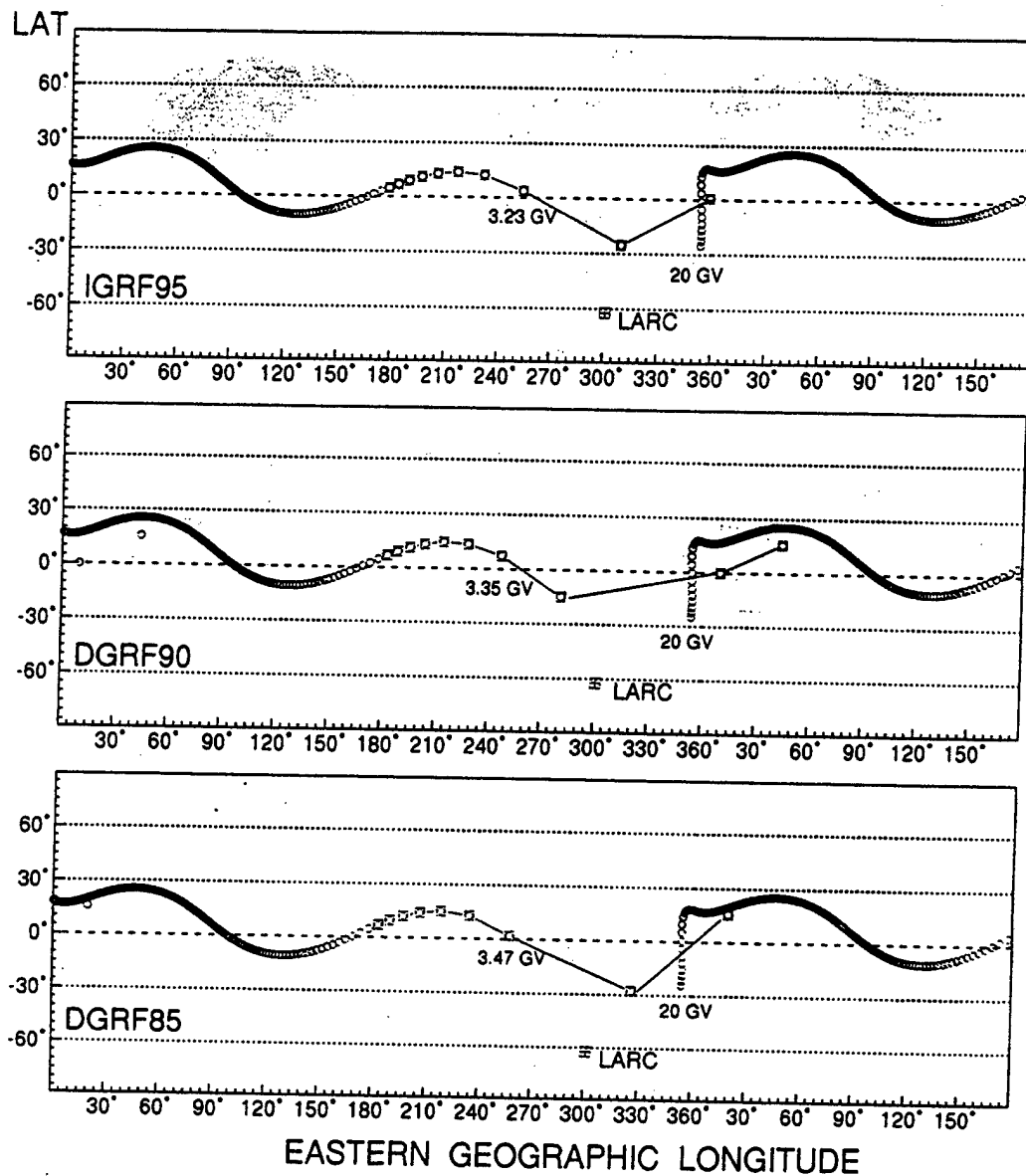
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Figure 4: Asymptotic directions for vertically incident cosmic ray particles at the LARC location as calculated using the DGRF85-DGRF90-IGRF95 geomagnetic field models (see the text for details).

Earth, particularly the Latin American, are affected by significant changes in cosmic ray cutoff rigidities (see also [13, 14, 15], among others). Cooper and Simpson [16], using the Huancayo neutron monitor data, confirmed such finding for Peru. Figure 5 illustrates the changing quiescent geomagnetic field from 1965 to 1995. The decrease in time of the magnetic field intensity at Huancayo implies an increased access to lower rigidity cosmic rays at the
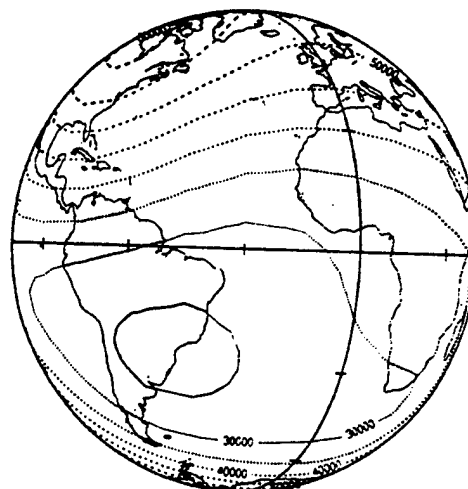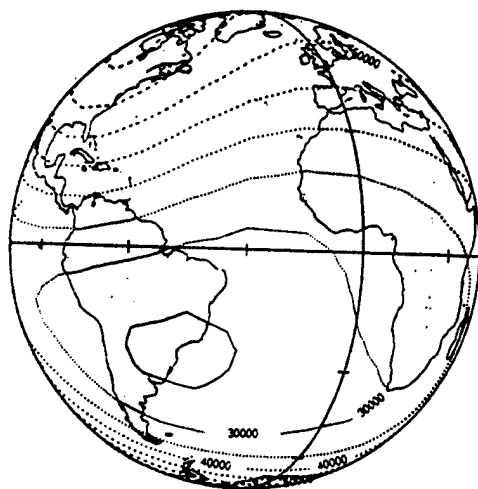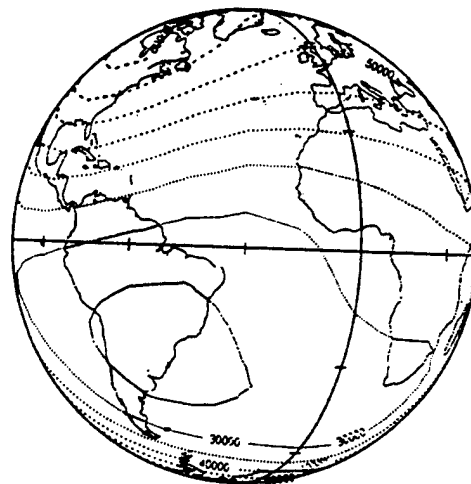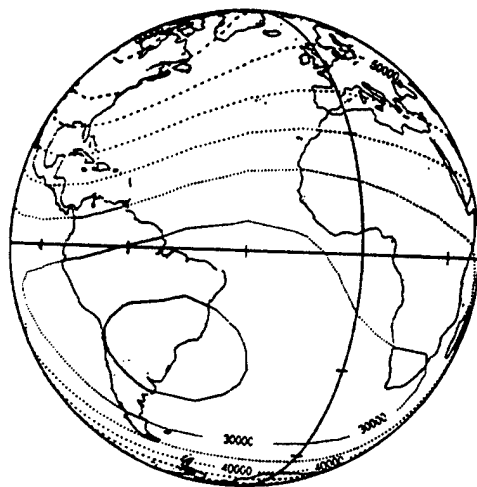
DGRF1965 - GEOMAGNETIC FIELD INTENSITY - F (nT)   DGRF1975 - GEOMAGNETIC FIELD INTENSITY - F (nT)

DGRF1985 - GEOMAGNETIC FIELD INTENSITY - F (nT)   IGRF1995 - GEOMAGNETIC FIELD INTENSITY - F (nT)

Figure 5: Contours of constant total geomagnetic field F at the surface of the Earth for 1965, 1975, 1985 and 1995, as derived from the standard geomagnetic reference field models. The contour intervals are every 5000 nT.

detection point. As a consequence, an increase in cosmic ray intensity over the years is expected and it was found. Nowadays the Huancayo detector is no more operated but other cosmic ray observatories are at work in the Latin American sector [17]. They should take into account the reported effect.

Figure 6, shows the field intensity and its components at LARC location for the interval 1955.0-2000.0, using one-year increment. They were derived using the Synthesis program (version 3.0) made available by NOAA. The
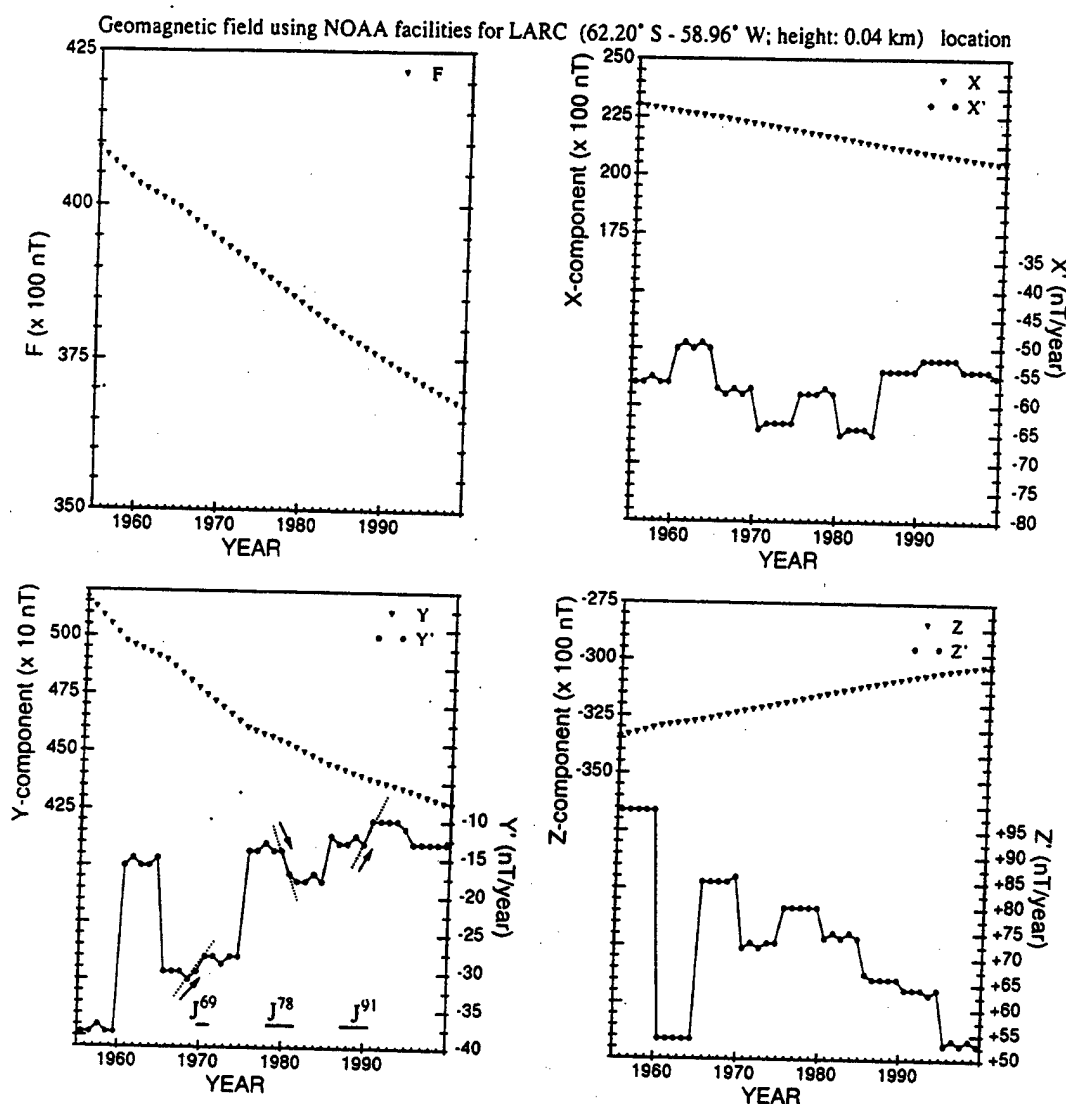
Figure 6: Long-term change of the F intensity, its components (X, Y, Z) and their derivatives (X', Y', Z') at LARC location. The time occurrence of 1969, 1978 and 1991 worldwide geomagnetic jerks (J[69], J[78], J[91]) is shown in lower left panel (after [4]: arrows indicate the corresponding Y' changes).

long term field variability at LARC is clearly emerging. Figure 6 (lower left panel) shows the occurrence of fast (< 5 years) variabilities (*geomagnetic jerks*) in the slope of the curve of the annual secular variation of the geomagnetic field (*e.g.* [18], and references therein). Their effects on the allowed cosmic ray rigidity spectrum at a measurement point should be further investigated.

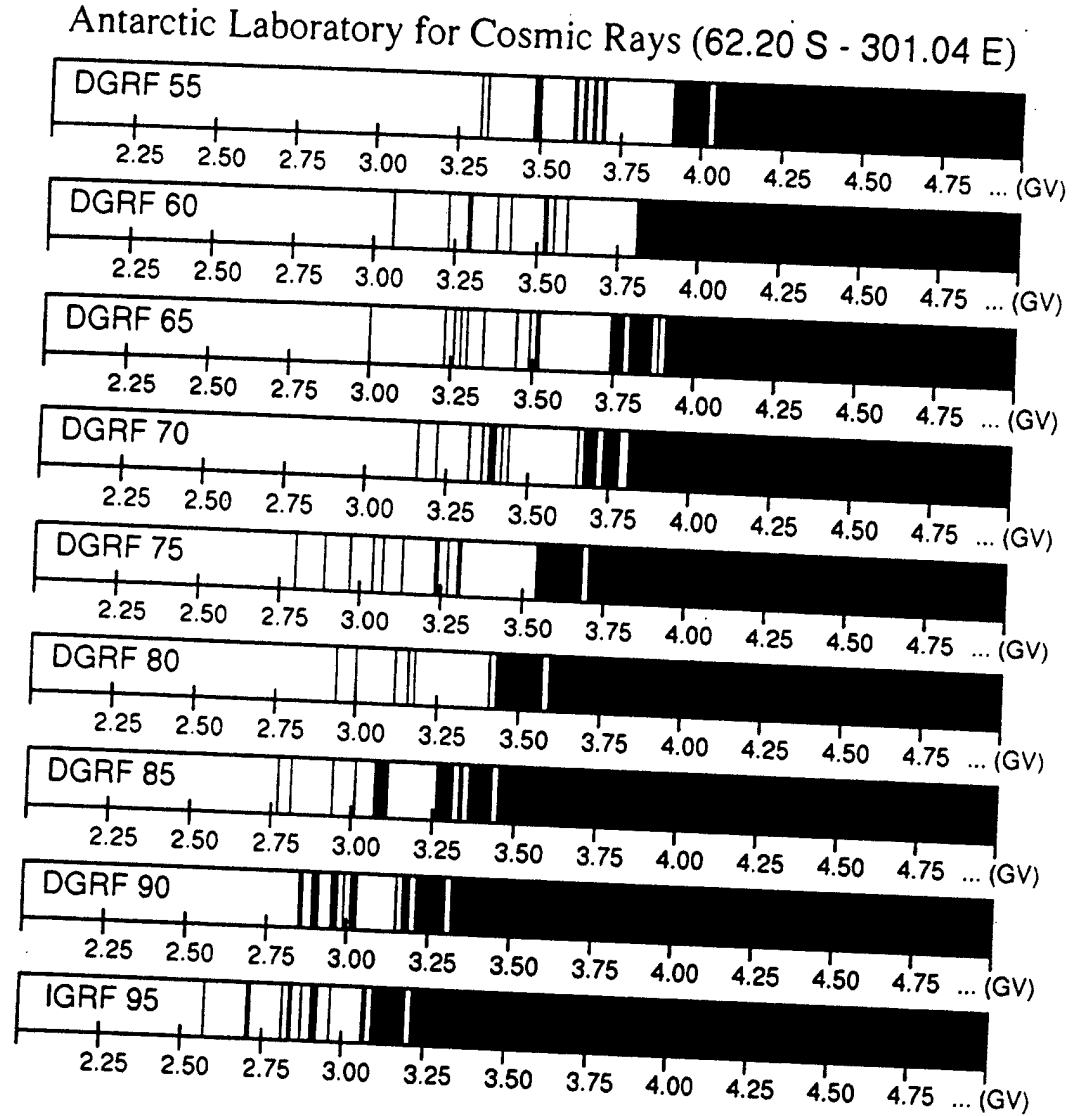The rigidity spectrum of allowed and forbidden particle rigidities in the

Figure 7: Charged particle access at LARC detector. Allowed particle rigidities are shown as dark areas and the forbidden one by white areas (after [4]).

interval 2.00 GV - 5.00 GV is reported in fig. 7 from 1955 (upper panel) to 1995 (lower panel) for LARC. As a consequence of the secular variations in the geomagnetic field, a decreasing trend in the LARC rigidity cutoffs (both in R_U and R_L) appears. Moreover, from fig. 7 we note that the cosmic ray penumbra does not change regularly in time. While R_U decreases nearly steadily from 1965 to 1995, the R_L values oscillate around the decreasing trend. Certainly, there is need for a better evaluation of possible effects
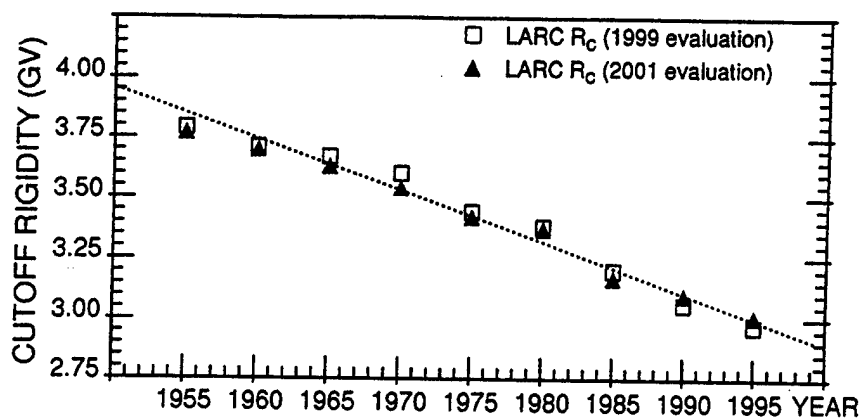
Figure 8: Results from R_C evaluation for LARC location based on the secular variation of the quiescent geomagnetic field (see the text for details). The data fit of the 1999 evaluation [4] is shown by a dashed line.

induced by the South-American geomagnetic anomalies and by the world wide geomagnetic jerks on the particle paths to LARC. Nevertheless, we have derived from them the effective vertical rigidity cutoff R_C at every epoch and they are reported by open squares in fig. 8. Recently, Shea and Smart [19] have computed vertical effective cutoff rigidities, from 1955 to 1995, for a long list of neutron monitor stations. LARC location was considered again; the new values are reported by filled triangles in fig. 8. From there, it is possible to confirm the decreasing trend of R_C (dashed line) at LARC, which should be considered in any long term study of the LARC records.

4 Conclusion

Using the appropriate Definitive Geomagnetic Reference Field coefficients for epochs 1955 to 1990 (DGRF55 to DGRF90) and the provisional ones for 1995 (IGRF95) the cosmic ray access to the LARC detector was studied for quiescent geomagnetic conditions. The obtained values testify a decreasing cutoff rigidity trend not only in the region of the so-called geomagnetic anomalies, as claimed in the past (see Sect. 3), but also Southward of it (i.e.. in the extreme Latin American sector), as it has been shown for the first time by Storini et al. [4]. The reported values should be considered as reference values for additional investigations.

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Acknowledgments

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